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Effects of Supersaturated Dissolved Atmospheric Gases on Northern Squawfish, Ptychocheilus oregonensis

Abstract

Northern squawfish, *Ptychocheilus oregonensis*, were confined in shallow tanks for 12 days to study their tolerance to various concentrations of total dissolved atmospheric gases (TDG). The TDG concentrations ranged from 100 to 126 percent of saturation—levels that occur in the Columbia and Snake Rivers downstream from dams during periods of high flow. Mortality did not occur in tests at or below 110 percent of saturation, but 32 percent of the fish succumbed in 12 days at 117 percent of saturation and 100 percent died in 20 hours at 126 percent of saturation. Average daily food consumption of squawfish decreased in proportion to increased saturation levels. At 100 percent of saturation (normal gas content), 14.2 g of food per fish per day were consumed; at 117 percent, 6.2 g; and at 120 percent, only 2.3 g per fish per day were consumed.

Field studies (1974 to 1976) indicated squawfish in the Snake River may not be seriously affected by supersaturation (from 117 to 141.5 percent of saturation). Gill-net drifts in the tailrace of dams showed that most squawfish were below the 3-m depth; therefore, they were at equilibrium and were unaffected by nitrogen supersaturation in the river. High TDG levels did not appear to hinder movement within 92 km of the study area. Purse seining adjacent to dams during spill closures indicated squawfish were actively feeding on fingerling salmon but probably did so from an equilibrated depth.

Introduction

Northern squawfish, *Ptychocheilus oregonensis*, have attracted the interest of many investigators because they are a major predator on valuable species of Pacific salmon, *Oncorhynchus* sp., and trout, *Salmo* sp. Hamilton *et al.* (1970), for example, reported that predation by squawfish was severe enough to preclude the use of Lake Merwin Reservoir, Washington, as a rearing area for coho salmon, *O. kisutch*. Brett and McConnell (1950), calculating losses of sockeye salmon, *O. nerka*, juveniles from Lakelse Lake, British Columbia, estimated that the consumption rate per squawfish was 140 salmon fingerlings per year. Thompson (1959) found that squawfish in the Columbia River were largely opportunistic in their feeding habits—7.5 percent of the squawfish stomachs examined for one year contained juvenile salmon, but in areas where migrating juvenile salmonids were prevalent, 51 percent of the adult squawfish fed on them.

Squawfish are present in large numbers in the lower Snake River, a principal

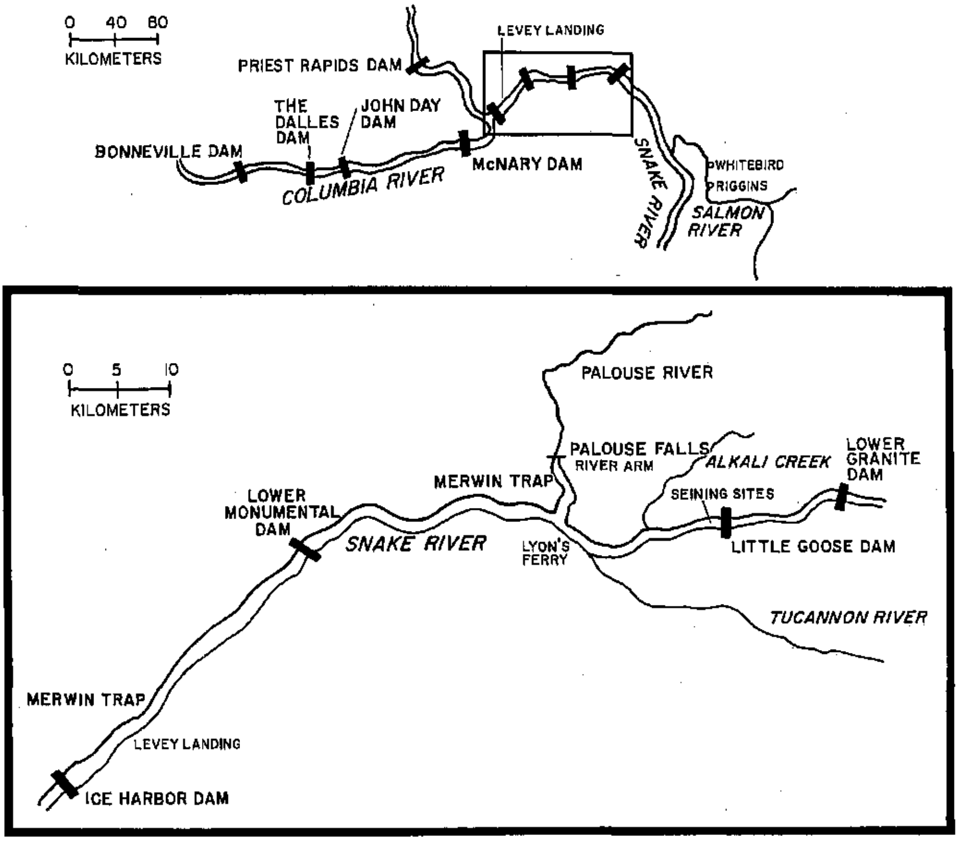

Figure 1. Dams on the Snake and Columbia Rivers from Little Goose to Bonneville. Detail shows squawfish catch areas.

tributary of the Columbia River (Fig. 1). Each spring millions of seaward migrating juvenile chinook salmon, *O. tshawytscha*, and steelhead trout, *S. gairdneri*, pass through the lower Snake River and could conceivably suffer substantial losses by squawfish predation. Long and Krcma (1969) measured a 33 percent loss of fingerlings related to predation by squawfish in the backroll and slackwater areas of the tailrace at Ice Harbor Dam.

In addition to losses caused by predation, supersaturation of dissolved gases in the water resulting from spilling at hydroelectric dams has caused significant losses in the past ten years of stocks of anadromous fish in the Columbia and Snake Rivers (Ebel, 1969, 1971). The relationship between squawfish predation and supersaturation of total dissolved atmospheric gases (TDG) was unknown at the time of Ebel's studies. Knowledge of the relationship between supersaturated water and squawfish predation could be important in making management decisions on dissolved gas control measures that are recommended by the fishery agencies. Meekin and Turner (1974) found that predation capabilities were substantially reduced at dissolved nitrogen concentrations of 120 percent of saturation and that mortalities occurred at 135 percent.

In our tests, we studied mortality rates for squawfish at various concentrations of supersaturation along with food consumption differences among the groups. A preliminary report on the first phase of this research was published by Bentley *et al.* (1976). Complete results of these tests and field observations of migration and feeding habits of squawfish in the Snake River are reported in the present paper.

Methods

Laboratory Tests

Adult squawfish (100) for the laboratory study were captured in the Snake River and transported by tank truck to the Northwest and Alaska Fisheries Center, National Marine Fisheries Service (NMFS), in Seattle, Washington. These fish were acclimated to the laboratory water at 10°C and normal TDG saturation (100 percent) and starved for 16 days before being introduced directly into the test tanks containing supersaturated water.

Six tests were conducted at average TDG concentrations of 126.1, 120.4, 117.2, 110.3, 107.2, and 99.8 percent of saturation. Simultaneous replicates were made of tests at 117.2, 110.3, and 99.8 percent of saturation. Nitrogen and oxygen concentrations were held to $\pm$ 4 percent of the TDG saturation value; standard deviations for daily dissolved gas data ranged from 0.5 to 3.1 percent TDG for the test duration of 12 days. All test tanks were 1.2 m in diameter with water depths of 25 cm (potential hydrostatic compensation 0.025 atmosphere of pressure, or about 2.5 percent of saturation). Water flow was maintained at 7.5 liter/min at 10°C $\pm$ 1° C. Lighting was controlled to simulate natural sunrise and sunset.

Tests began on 17 April 1974, and were conducted with about 10 fish per tank. The mean length and weight of the test fish at introduction was 364 mm and 534 g, respectively. Prior to the actual tests, a sample population was fed to determine the maximum weight of food an unstressed fish might consume in a 2-wk period. On the basis of food intake of the sample population, we established a daily ration for test groups of four dead eulachon, *Thaleichthys pacificus* (average size: 170 mm, 30 g), and one live steelhead trout (average size: 80 mm, 21 g) for each test tank. One-half of the eulachon introduced as food were cut in half to accommodate the smaller squawfish.

During the tests, fish groups were observed for behavioral changes, with particular regard to their food intake. Daily measurements of dissolved gas concentrations were performed, using gas chromatography calibrated for nitrogen plus argon with a manometric blood gas analyzer (Van Slyke and Neil, 1924) and for oxygen with the Winkler titration (American Public Health Association *et al.*, 1971). Dead fish were taken from test tanks twice daily, weighed, measured, and examined for signs of gas bubble disease. All fish were examined at the end of the test period for internal and external signs of gas bubble disease.

Field Observations

During 1974, 1975, and 1976, adult squawfish were collected from the Snake River to examine their food intake, movement, and vertical distribution in relation to varying levels of dissolved gas supersaturation in the river. Captured fish were anesthetized, measured, and checked for food intake and signs of gas bubble disease symptoms.

They were then marked and returned to the river. Marking was accomplished with either a Floy anchor tag, FD67,[1] or branding (Mighell, 1969).

Squawfish were collected from the Snake River by purse seines and gill nets in the tailrace of Little Goose Dam. They were also collected from Lake Merwin traps (Hamilton *et al.*, 1970) in the Palouse River Arm, 20 km downstream from the dam, and at Levey Landing, 92 km downstream from Little Goose Dam (Fig. 1). The Merwin trap in the Palouse River Arm was operated seasonally from November 1973 to 1 July 1976 and the trap at Levey Landing, from October 1974 to 1 July 1976. Purse seining was done at Little Goose Dam from 24 April to 8 August 1974, and at Lower Granite Dam from 6 May to 23 June 1976. Gill-net drifts in the tailrace area of Little Goose Dam were made from 25 April to 22 May 1975.

Purse seining was done with a net 4.6 m deep and 160 m long; it was operated from a power-driven barge using a technique similar to that described by Durkin and Park (1967). The drifted gill net was 91.4 m long by 6.7 m in depth with a stretched mesh of 6.35 cm. The technique was to get as close to the spill as possible. When the boat was in position, the engine was put in reverse. While the boat was backing across the wake of the spill, the gill net was fed into the water through rollers in the bow. After the net was all out, the boat drifted with the net for about 1200 m downstream. The net was usually set perpendicular to the spill current.

Food intake was measured from fish taken in 1976 by purse seines in the tailrace of Lower Granite Dam. Accurate measures were not possible at Little Goose Dam during the first two years of the study because high spill and turbulence during the fingerling seaward migration prevented adequate sampling in the tailrace. By 1976, a method of controlling spill at Lower Granite Dam was developed wherein the spill was shut off for short periods to permit adequate sampling in the tailrace.

Depth distribution of squawfish was determined from samples taken by gill nets in 1975. A black marker line was sewed at the 3-m depth to ascertain with accuracy whether a captured squawfish was above or below the depth which generally insured safety from the effects of supersaturation in the Snake River (Ebel, 1969, 1971). We assumed depth distribution was similar in 1976 to that measured in 1975.

Water samples were taken biweekly between April and August from 1974 to 1976 to study the concentration of dissolved gases in the Snake River. Analyses were made at the NMFS Northwest and Alaska Fisheries Center.

Results

Laboratory Tests

Mortality and Signs of Gas Bubble Disease. Substantial mortality of squawfish occurred in tests at high supersaturation concentrations but did not occur in tests at or below 110 percent of saturation. One hundred percent mortality occurred in 20 h at 126 percent of saturation; 60 percent loss occurred within the 12-d test period at a concentration of 120 percent; and 32 percent loss occurred within the 12-d test period at 117 percent of saturation. Lethal exposure times to 10 and 50 percent mortality (LE_{10} and LE_{50}) for squawfish are compared in Table 1 with LE_{10} and LE_{50} values

[1]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

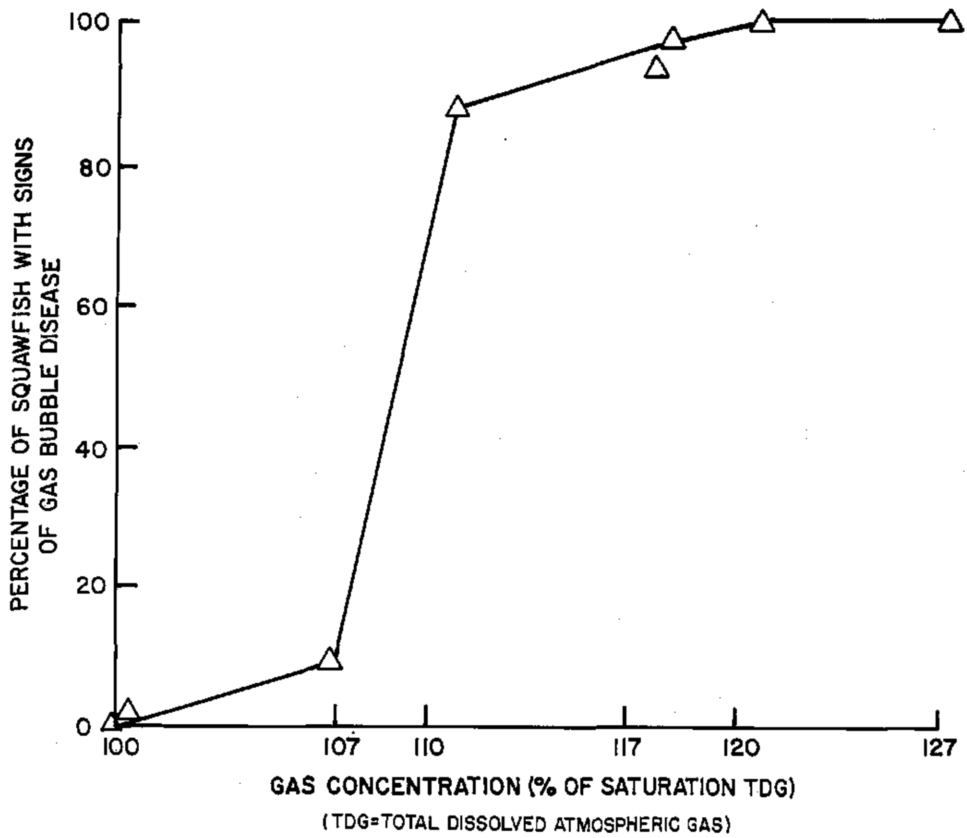

Figure 2. Percentage of squawfish with signs of gas bubble disease after death or after surviving 12 days of exposure to various concentrations of dissolved gas in laboratory tests.

established for their potential salmonid prey (Dawley and Ebel, 1975; Dawley *et al.*, 1976). Evidently squawfish are more tolerant to supersaturation of dissolved gas than juvenile steelhead trout and spring chinook salmon, but they are much less resistant than fall chinook salmon fry.

Signs of gas bubble disease were found in all fish exposed to 126, 120, and 117 percent of saturation (Fig. 2). Of the squawfish exposed to 110 percent of saturation,

TABLE 1. Comparison of lethal exposure times to 10 and 50 percent mortality (LE_{10} and LE_{50}) for squawfish and potential salmonid prey at different concentrations of dissolved gas in shallow tanks.

Total dissolved gas concentration (% saturation)	Adult squawfish (364 mm, 534 g) 10°C		Juvenile steelhead trout (135 mm, 20 g) 15°C		Juvenile spring chinook salmon (120 mm, 15 g) 15°C		Juvenile fall chinook salmon (42 mm, 0.4 g) 10°C	
	LE_{10} (h)	LE_{50} (h)	LE_{10} (h)	LE_{50} (h)	LE_{10} (h)	LE_{50} (h)	LE_{10} (h)	LE_{50} (h)
115	—	—	—	—	—	—	480	1128
117	115	>228*	26	33	19	27	—	—
120	41	233	10	14	11	14	168	528
126	19	20	—	—	—	—	—	—

*Test groups sustained a mean of 29% mortality in 228 h.

89 percent had gross signs of gas bubble disease; 1 of 10 fish exposed to 107 percent of saturation exhibited signs. No signs were noted among the fish exposed to 100 percent saturation. Gross gas bubble disease signs included hemorrhage and subcutaneous gas blisters over large areas of the body. All fish showing signs of gas bubble disease exhibited greatly distended gas blisters between the fin rays. Exophthalmia ("popeye") occurred in only two fish. Gaseous emboli were noted in the blood vessels of at least one gill arch in all dead fish. Emboli were also observed in the gill filaments of all squawfish surviving the test at 120 percent of saturation and many surviving the tests at 117 percent. Emboli within the gill filaments were not detected in squawfish exposed to lower supersaturation concentrations.

Feeding Activity. Active feeding decreased by about 84 percent, from an average of 14.3 g of food per fish per day for squawfish exposed to 100 percent (normal) saturation to an average 2.3 g of food per fish per day when squawfish were exposed to 120 percent of saturation (Fig. 3). These data also indicated that food uptake by

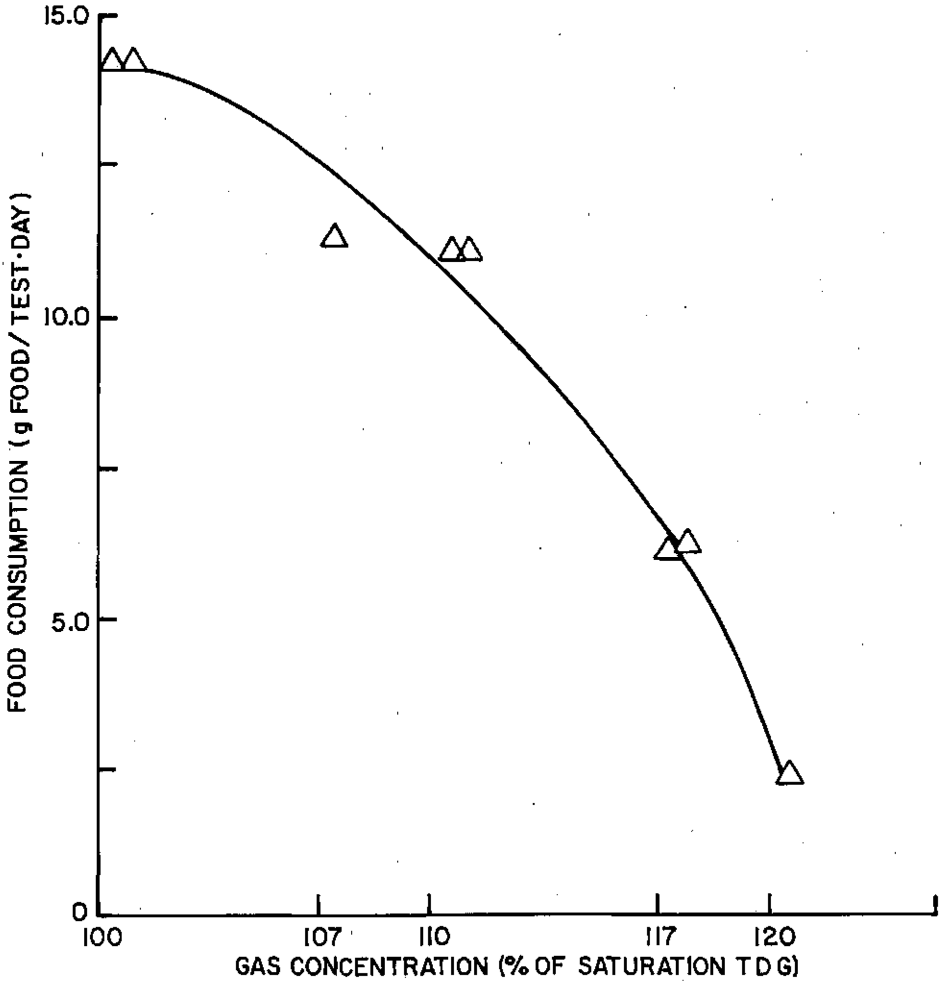

Figure 3. Average daily food consumption of squawfish exposed to different dissolved gas concentrations for 12 days in laboratory tests (TDG = total dissolved atmospheric gas).

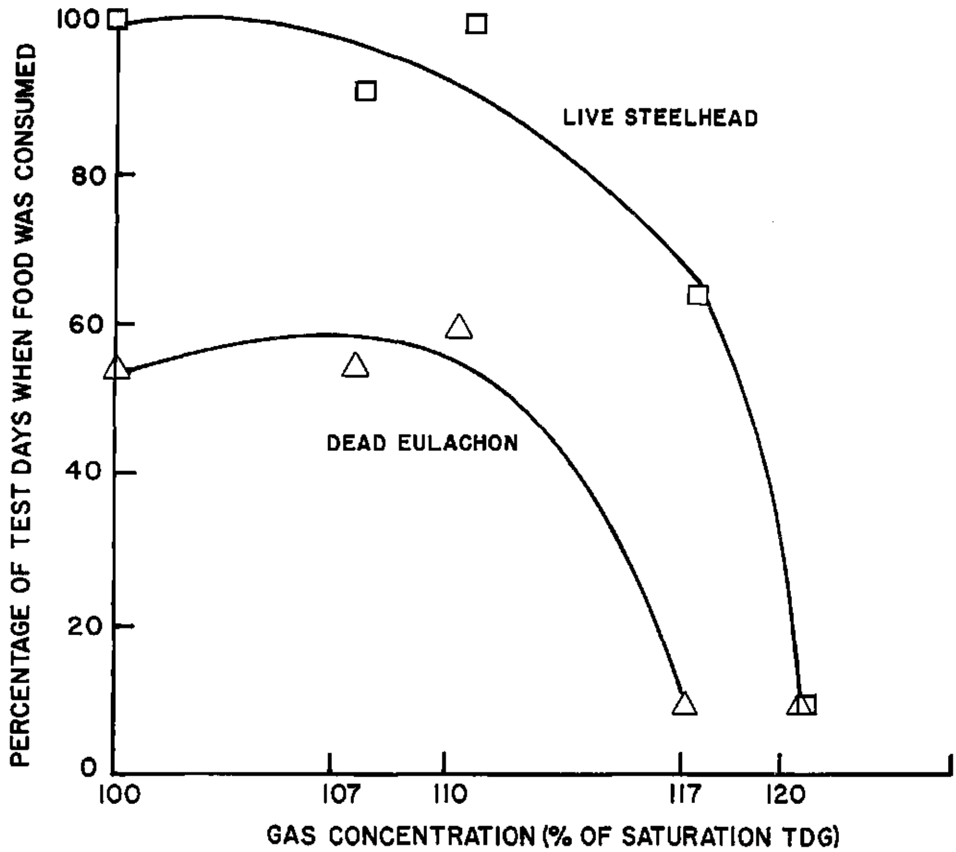

Figure 4. Percentage of days during laboratory test when food ration was completely consumed by squawfish in relation to different dissolved gas concentrations (TDG = total dissolved atmospheric gas).

squawfish would be reduced from normal by about 50 percent when the concentration of TDG reached 115 percent of saturation. At concentrations below 117 percent, squawfish showed a preference for consuming live steelhead trout rather than dead eulachon (Fig. 4). Squawfish held at 120 percent of saturation consumed no live steelhead trout after the first day of testing. At 117 percent of saturation, the consumption of live steelhead trout was reduced 40 percent compared to the control.

The inability or unwillingness of squawfish stressed by supersaturation to catch and consume live steelhead trout may be affecting predation on juvenile salmonids migrating downstream in the Columbia and Snake Rivers. Our laboratory tests, however, were accomplished in shallow tanks allowing no potential hydrostatic compensation from the effects of supersaturation. Measurements made on the river in 1976, where there was sufficient depth to equilibrate, provided additional data on predation rate in supersaturated water. These data will be discussed later.

Field Observations

Movements of Squawfish Relative to Dissolved Gases. A total of 23,046 squawfish were captured, tagged, and released from the trap in the Palouse River Arm from

November 1973 to 1 July 1975. A total of 2729 squawfish were captured, tagged, and released from the trap at Levey Landing from October 1974 to 1 July 1975. Between April 1974 and 1 July 1975, 2859 squawfish were collected, tagged, and released from purse-seine and gill-net sampling below Little Goose Dam. Subsequent recaptures of tagged fish provided data on their migration behavior during varying concentrations of supersaturation (up to 141.5 percent of saturation) in the Snake River in 1974 and 1975 (Table 2).

TABLE 2. Temperature, dissolved gas concentrations, spill volume, and total water flow at Lower Monumental and Little Goose Dams from April to August 1974 and from April to July 1975.

	Little Goose Dam forebay Saturation (%)						Lower Monumental Dam forebay Saturation (%)					
Date	Temp (°C)	O_2	$N_2 + Ar$	TDG*	Spill**	Total river flow (km^3/s)	(°C) Temp	O_2	$N_2 + Ar$	TDG*	(km^3/s) Spill**	Total river flow (km^3/s)
1974												
4/19	8.3	99.6	101.4	101.0	2.43	3.71	8.5	117.8	122.1	120.9	2.35	4.25
4/23	9.6	102.5	106.8	105.8	1.73	3.68	9.9	130.8	134.6	133.3	1.67	3.57
5/7	11.6	105.9	110.3	109.2	2.72	4.59	12.1	130.8	135.8	134.2	2.69	4.64
5/21	11.4	98.5	104.1	102.8	0.48	2.35	11.3	114.2	121.5	119.7	0.42	2.26
6/4	12.2	99.2	102.9	102.0	2.60	4.55	11.9	127.9	141.1	137.7	2.55	4.50
6/19	12.8	102.4	111.5	109.4	6.45	8.49	12.5	128.7	143.8	140.0	6.22	8.32
7/2	16.9	99.5	106.8	105.1	0.0	3.57	16.7	124.6	131.8	129.8	1.87	3.77
7/16	17.4	103.4	106.7	105.9	0.54	1.78	19.0	102.4	106.4	105.5	0.08	1.93
7/30	24.5	117.7	110.3	111.5	0.0	1.33	23.2	110.3	106.7	107.2	0.0	1.24
8/13	21.7	99.4	104.9	103.7	0.0	1.25	21.7	101.8	105.8	104.9	0.0	1.22
1975												
4/8	7.6	121.6	113.8	115.2	0.42	1.64	7.6	122.2	110.6	112.9	0.0	1.81
4/22	9.9	128.4	118.0	119.9	0.70	2.54	9.6	120.1	114.5	115.5	0.76	2.56
5/6	10.0	112.2	111.4	111.4	0.53	2.40	10.5	124.2	125.0	124.5	1.10	2.40
5/20	13.4	124.7	128.1	125.4	3.85	5.12	12.7	138.2	139.6	138.3	3.37	4.64
6/3	13.2	112.9	118.5	117.0	3.37	5.26	14.0	128.3	134.5	132.7	3.05	4.92
6/17	12.8	114.0	121.1	119.3	2.86	5.23	13.9	130.4	140.9	138.0	1.78	3.68
7/1	13.5	116.8	121.9	120.5	1.58	3.42	14.1	137.6	143.4	141.5	1.30	3.17

*TDG = Total dissolved atmospheric gases.

**Water flow data entered in thousands of cubic meters per second (km3/s).

Most upstream movement of squawfish occurred after spilling had ceased and gas concentrations had returned to normal. Of approximately 17,000 fish tagged in the Palouse River Arm between April and June 1974, only four were recovered in the tailrace of Little Goose Dam during supersaturation conditions, compared to recovery of 101 after gas concentrations had returned to normal (Table 3). However, substantial numbers of squawfish did move downstream during periods of high dissolved gas concentrations. Seventeen of the fish tagged at Little Goose Dam were recovered downstream in the trap at the Palouse River Arm and three further downstream in the trap at Levey Landing; i.e., 20 km and 92 km downstream, respectively, from the tagging site. Twenty-six of the fish tagged in the Palouse River Arm were subsequently recovered downstream in the trap at Levey Landing.

All downstream recoveries were made when concentrations of TDG were high. Obviously these fish must have traveled at a depth which compensated for high

TABLE 3. Movements of squawfish between areas in 1974 and 1975 during periods of high dissolved gases (>120% of saturation) and low dissolved gases (<120% of saturation).

Area	No. squawfish moving in high TDG* concentrations (>120% of saturation) April through June	Distance between sites (km)	Average no. days since tagged	No. squawfish moving in lower or normal TDG concentrations (<120% of saturation) July through March	Average no. days since tagged
Little Goose Dam to Palouse Trap	17	20	215	31	111
Little Goose Dam to Levey Trap	3	92.5	24	0	—
Palouse Trap to Little Goose Dam	4	20	207	101	141
Palouse Trap to Levey Trap	26	72.7	166	4	168
Levey Trap to Little Goose Dam	2	92.5	18	0	—
Levey Trap to Palouse Trap	2	72.7	155	0	—
	54			136	

*TDG = total dissolved gas.

dissolved gas concentrations recorded near the surface at the time. If they had traveled in the upper 3 m of water where gas concentrations would have been greater than 110 percent of saturation, they could not have survived the journey (based on laboratory test data).

Depth Distribution. Gill nets drifted through the tailrace of Little Goose Dam from 25 April through 22 May 1975 captured 290 squawfish in eight drifts (Table 4). Dissolved gas levels during this period ranged between 116 and 130 percent of saturation. Only five fish were above the 3-m marker, indicating that less than 2 percent were in the lethal area of supersaturated concentrations at the time of capture.

TABLE 4. Depth at which squawfish were caught by drifting gill nets in the tailrace of Little Goose Dam from 25 April through 22 May 1975.

Date	No. gill net drifts	No. squawfish caught Below 3-m depth	Above 3-m depth
April			
25	3	—	—
May			
2	1	58	0
8	1	60	3
16	2	132	2
22	1	35	0
Total	8	285	5

However, 46 percent showed signs of gas bubble disease, suggesting that they spent part of their time during this period in surface areas.

Feeding Activity. We purse seined in the tailrace of Little Goose Dam in 1974 during the seaward migration of salmonids when TDG concentrations in the river were high (Table 2); 5 out of 176 squawfish taken showed evidence of feeding (Table 5). When dissolved gas content returned to near normal concentrations, 100 percent of the squawfish examined were shown to be feeding heavily on Pacific lamprey ammocetes, *Entosphenus tridentatus*, and unidentified fish (Table 5).

At Lower Granite Dam in 1976 over 2600 squawfish were captured in 32 purse seine sets during the salmonid fingerling seaward migration (Table 6). Spilling was

TABLE 5. Fishing effort, catches, and observed stomach contents of squawfish captured by purse seining in the tailrace area at Little Goose Dam during periods of high and low dissolved gas concentrations in 1974.

Gas condition	Date	No. of sets	No. of squawfish captured	No. of squawfish containing food organisms	Type of food
High*	April 24	2	3	0	—
	25	4	26	1	unident. fish
	May 3	1	22	0	—
	16	2	12	0	—
	30	3	17	2	unident. fish
	31	2	18	0	—
	July 12	1	78	2	unident. fish
		15	176	5	
Low**	July 17	2	26		
	18	3	398		
	31	4	125		
	August 2	1	542	100	lamprey or
	6	1	699	examined	unidentified fish
	8	1	145		—
		12	1935	100	

*Concentration of dissolved gas ranged from 120 to 140% of saturation (TDG).

**Concentration of dissolved gas ranged from 105 to 107% of saturation (TDG).

TABLE 6. Fishing effort, catches, and observed stomach contents for adult squawfish (fish greater than 180 mm long) captured by purse seining in the tailrace area at Lower Granite Dam in 1976.

Date	Purse seine sets	Total no. squawfish Eddy	Spill	Power house	Lock	No. adult squawfish* Catch	With salmon	Predation index**
5/6***	5	87	7	0	0	29	8	27.6
5/13	5	98	0	0	0	13	1	7.7
5/19	3	257	0	0	0	90	2	2.2
5/21	2	167	0	0	0	62	2	3.2
5/26	3	473	0	0	0	360	52	14.4
6/2	3	114	0	0	27	40	12	30.0
6/4	4	111	0	0	0	27	9	33.3
6/8	2	261	0	0	0	149	48	32.2
6/10*	4	432	16	0	0	342	91	26.6
6/23	1	684	0	0	0	330	83	25.2
Total	32	2684	23	0	27	1442	308	Avg. 21.4%

*Longer than 180 mm.

**Index = No. of squawfish with salmon/no. of squawfish <180 mm.

***Controlled closure of spill gates.

continuous except during short periods when the spill was shut down to permit sampling. Dissolved gas concentrations ranged between 117 and 124 percent of saturation during the sampling period. Of the 1442 adult squawfish stomachs examined, 21 percent contained salmon; further examination of these stomach contents revealed that the majority of squawfish had consumed fingerling salmon before they were captured, indicating that active predation was occurring. This determination was made by examining the degree of decomposition of the prey in the digestive tract. Any decomposition would indicate predation in the wild before capture rather than feeding on fingerling salmon also captured in the seine.

Population Estimates and Predation Rates. During April, May, and June 1974, 17,664 squawfish were collected, tagged, and released in one small area of the Snake River (Palouse River Arm); 2583 or 15 percent were subsequently recaptured. The mean Petersen estimate (Chapman, 1952) indicated a population of about 117,600 fish. If similar numbers were present in other reservoirs, the total could approach 400,000 fish for the stretch of the Snake River between Lower Granite and Ice Harbor Dams.

During a low-flow year with no spill over the dams, the entire seaward migration of juvenile chinook salmon must pass through turbines. Although direct mortality through turbines is less than 15 percent at each dam (Schoeneman *et al.*, 1961), many fish are crippled or stunned and vulnerable to predators (Long and Krcma, 1969). Four hundred thousand squawfish could easily consume a significant fraction of the four to five million chinook salmon juveniles annually migrating down the Snake River under these conditions. This event may have occurred in the low-flow year of 1973 when Raymond (1974) measured an 88 percent mortality between Little Goose Dam and Ice Harbor Dam.

During higher flow years, much of the seaward migration passes over the spill with minimum mortality and stunning (Schoeneman *et al.*, 1961). Moreover, those passing through turbines are provided the additional protection of turbulence and high turbidity. In the high flow years of 1971 and 1974, only a 50 percent mortality was measured between Little Goose and Ice Harbor Dams, largely the result of prolonged exposure to high levels of TDG saturation instead of predation (Raymond, 1974). Spillway deflectors, installed at Lower Granite and Lower Monumental Dams in 1975 to reduce gas saturation, reduced mortality to 33 percent between Lower Granite and Ice Harbor Dams (Ebel and Raymond, 1976).

Conclusions

Based on laboratory studies in shallow tanks (0.25 m in depth), adult northern squawfish were severely affected—high mortality, physical impairment, and decreased ability to feed—when exposed to TDG concentrations 117 percent of saturation and above.

Field studies generally corroborated findings in the laboratory. However, below the tailrace of the dams, we found that most squawfish resided at depths below 3 m where they would be equilibrated to high gas saturation and could make quick foraging trips to the surface and back to depth without any serious gas problems. This finding indicated that predation during high concentrations of supersaturation may be even greater than expected.

Continued assessment of squawfish abundance, food consumption, and distribution under different levels of TDG saturation is needed to measure accurately the effect on the survival of juvenile salmon and steelhead trout.

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